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AIR FORCE SYSTEMS COMMAND

COMBINED PLUS INTEGRAL CONTROL IN THE SERVO SYSTEMS

by

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FOREIGN TECHNOLOGY DIVISION

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

Page 188.

COMBINED PLUS INTEGRAL CONTROL IN THE SERVO SYSTEMS.

B. V. Novoselov.

I. Formulation of the problem.

In the practice of automatic control wide application obtained the servo systems of the combined control (SSKR) (Fig. 1A), which together with many positive properties possess a number of the essential deficiencies/lacks:

for satisfaction of the conditions of invariance it is necessary to measure and to differentiate the input effect (VV);

the conditions of invariance require the strictly defined relationships/ratios between the levels of the compensating signals (KS) and the parameters of main circuit SSKR;

the limited number of derivatives of VV, ensuring the

compensation for the steady errors into some modes of operation SSKR, can lead to an increase in the errors in other operating modes;

- the presence of derivatives of VV can cause an increase in the error SSKR in the presence of interference at the input and excessively increase the oscillation property of system with the changes in VV.

In this work is examined one of the ways of an improvement in the quality of SSKR in the presence in it of KS on one derivative of alone VV.

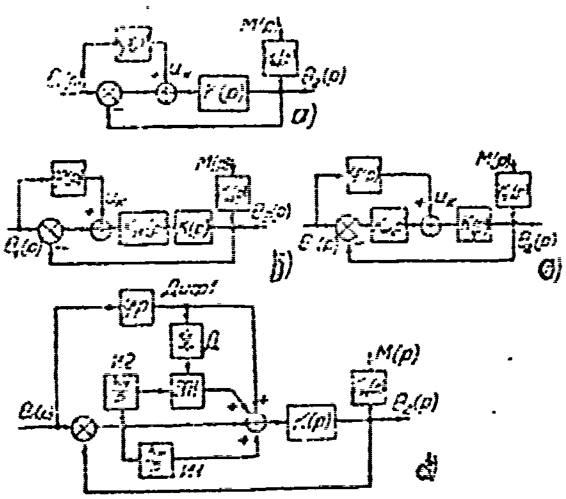

Fig. 1. Block diagrams of SSKR.

Page 189.

In diagram in Fig. 1A

$$\varphi(p)=\varphi p;\quad K(p)=\frac{K}{p(1+T_1p)(1+T_2p)}. \tag{1.1}$$

In this system of the expression of errors Θ_κ, Θ_∂, for proportional ones with respect to rate Ω_1 and acceleration ε_1 VV, they take the form

$$\Theta_\kappa = C_1\Omega_1 = \Omega_1\lim_{p\to 0}\frac{1}{p}\Phi_\omega(p) =$$

$$=\Omega_1\lim_{p\to 0}\frac{1}{p}\,\frac{p(1+T_1p)(1+T_2p)-K\varphi p}{p(1+T_1p)(1+T_2p)+K} = \Omega_1\frac{1-K\varphi}{K}; \tag{1.2}$$

$$\Theta_\partial = C_2\varepsilon_1 = \varepsilon_1\lim_{p\to 0}\frac{1}{p^2}\left[\Phi_\omega(p)-C_1p\right] =$$

$$=\varepsilon_1\,\frac{K(T_1+T_2)-1+K\varphi}{K^2}. \tag{1.3}$$

In the stationary parameters of SSKR:

if $$\varphi = \frac{1}{K},\ \text{то}\ \theta_\kappa = 0,\ \theta_\partial = \frac{T_1+T_2}{K}\varepsilon_1; \tag{1.4}$$

if. $$\varphi = \frac{1-K(T_1+T_2)}{K},\ \overset{(1)}{\text{то}}\ \theta_\kappa = (T_1+T_2)\Omega_1,\ \theta_\partial = 0. \tag{1.5}$$

Key: (1) that.

Fig. 2a, b depicts the oscillograms of work of SSKR during two tuning

$$\varphi = \frac{1}{K}\ \overset{(1)}{\text{и}}\ \varphi = \frac{1-K(T_1+T_2)}{K}.$$

Key: (1) and.

On the basis of (1.4), (1.5) and Fig. 2a, b it follows that by changing tuning of KS in such a way that with VV $\theta_1(t)=\Omega_1 t$ would be ensured relationship/ratio $\varphi = \frac{1}{K}$, and with VV $\theta_1(t) = \frac{\varepsilon_1 t^2}{2}$ - relationship/ratio $\varphi = \frac{1-K(T_1+T_2)}{K}$, it is possible in the presence of KS only on one derivative of VV to ensure compensation θ_κ, θ_∂.

For guaranteeing the minimum of the sum of the squares of errors θ_κ and θ_∂

$$\theta_\Sigma^2 = \theta_\kappa^2 + \theta_\partial^2 = \Omega_1^2\frac{1-2K\varphi+K^2\varphi^2}{K^2} + \varepsilon_1^2\frac{K^2(T_1+T_2)^2-2(1-K\varphi)K(T_1+T_2)+(1-K\varphi)^2}{K^4} \tag{1.6}$$

it is necessary, on the basis of the condition

$$\frac{\partial\theta_z}{\partial\varphi}=\Omega_1^2\frac{2K^2\varphi-2K}{K^2}+\varepsilon_1^2\frac{2K^2(T_1+T_2)+2K^2\varphi-2K}{K^4}=0, \qquad (1.7)$$

to ensure tuning of KS according to the law

$$\varphi=\frac{\frac{1}{K}-(T_1+T_2)+K\frac{\Omega_1^2}{\varepsilon_1^2}}{1+K^2\frac{\Omega_1^2}{\varepsilon_1^2}}. \qquad (1.8)$$

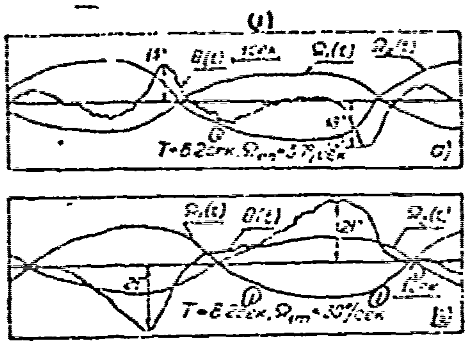

Fig. 2. Oscillograms of work of SSKR.

Key: (1). s.

Page 190.

If $K^2\frac{\Omega_1^2}{\varepsilon_1^2}\gg 1$, then law (1.8) takes the form

$$\varphi = \frac{\varepsilon_1^2}{\Omega_1^2 K^2}\left[\frac{1}{K} - (T_1 + T_2)\right] + \frac{1}{K} \qquad (1.9)$$

During the final adjustment of VV of form $\theta_1(t) = \theta_{1m}\sin\omega t$ for guarantee $\theta_2^2 = \min$ it would be necessary to change φ according to laws (1.8) or (1.9), but for this is necessary measurement ε_1, which is virtually complicated. Moreover, measurement ε_1 would make it possible to carry out the combined control (KU) on two derivatives of VV, which would ensure in the stationary parameters SSKR $\theta_v = 0$, $\theta_a = 0$.

In the presence only of one derivative of VV it is expedient,

which will shown below, for guaranteeing the high accuracy in the modes/conditions of the final adjustment of VV of form $\theta_1(t)=\Omega_1 t,\ \theta_1(t)=\frac{\varepsilon_1 t^2}{2},\ \theta_1(t)=\theta_{1m}\sin\omega t$ (ω<1) supplement of KU by the integral control (IU) (Fig. 1b, c). In the present work are examined the results of experimental final adjustment of SSKR with IU and are indicated the ways of further improvement in the quality of systems of this type.

2. Investigation of SSKR with IU.

Is possible realization SSKR with IU on the diagrams in Fig. 1b and 1c, where

$$K(p)=\frac{K}{p(1+T_1p)(1+T_2p)},\quad \varphi(p)=\varphi p,$$
$$K_{И}(p)=K_0+\frac{K_{И}}{p}. \tag{2.1}$$

The transfer function of locked SSKR with IU and expression of error during the final adjustment of VV they take the form: for the diagram in Fig. 1b

$$\Phi(p)=\frac{\theta_2(p)}{\theta_1(p)}=\frac{K(p)K_{И}(p)[1+\varphi(p)]}{1+K(p)K_{И}(p)}=$$
$$=\frac{K(K_0p+K_{И})(1+\varphi p)}{p^2(1+T_1p)(1+T_2p)+KK_0p+KK_{И}}, \tag{2.2}$$
$$\theta(p)=\theta_1(p)\frac{T_1T_2p^4+(T_1+T_2)p^3+(1-KK_0\varphi)p^2-KK_{И}\varphi p}{p^2(1+T_1p)(1+T_2p)+KK_0p+KK_{И}}, \tag{2.3}$$

for the diagram in Fig. 1c

$$\Phi(p)=\frac{\Theta_2(p)}{\Theta_1(p)}=\frac{K(p)[\varphi(p)+K_И(p)]}{1+K_c p)K_И(p)}=$$
$$=\frac{K(K_c p+K_И+\varphi p^2)}{p^2(1+T_1 p)(1+T_2 p)+KK_c p+KK_И}, \quad (2.4)$$
$$\Theta(p)=\Theta_1(p)\frac{T_1T_2p^4+(T_1+T_2)p^3+(1-K\varphi)p^2}{p^2(1+T_1p)(1+T_2p)+KK_c p+KK_И} \quad (2.5)$$

The transfer functions of closed system relative to the moment disturbance/perturbation M(t) for the diagrams in Fig. 1b and 1c are identical

$$\Phi_M(p)=\frac{\Theta_2(p)}{M(p)}=\frac{W_M(p)}{1+K_И p)K(p)}=$$
$$=\frac{K_M p(1+T_1p)M(p)}{p^2(1+T_1p)(1+T_2p)+KK_c p+KK_И}. \quad (2.6)$$

According to (2.6) in SSKR with IU during the constant disturbance/perturbation M(t)=M=const moment error $\Theta_M=C_M M=0$.

Page 191.

From analysis (2.2)-(2.5) it follows that in the stability the diagrams in Fig. 1b and 1c identical, but are different in the accuracy and the oscillation property during the final adjustment of VV.

For the diagram in Fig. 1b

$$\Theta_к=-\Omega_1\varphi,\ \Theta_д=\frac{\varepsilon_1}{KK_И};$$

for the diagram in Fig. 1c

$$\Theta_к=0,\ \Theta_д=\varepsilon_1\frac{1-K\varphi}{KK_И}. \quad (2.7)$$

In the diagram in Fig. 1b in any modes/conditions $\Theta_x=0$, $\Theta_\rho\neq0$. In the diagram in Fig. 1b $\Theta_x=0$ in all modes/conditions, $\Theta_\rho=0$ when $\xi=\frac{1}{\lambda}$. On the graphs/curves of Fig. 3a-3e are represented the results of the experimental investigation of SSKR with IU, carried out on the diagram in Fig. 1c.

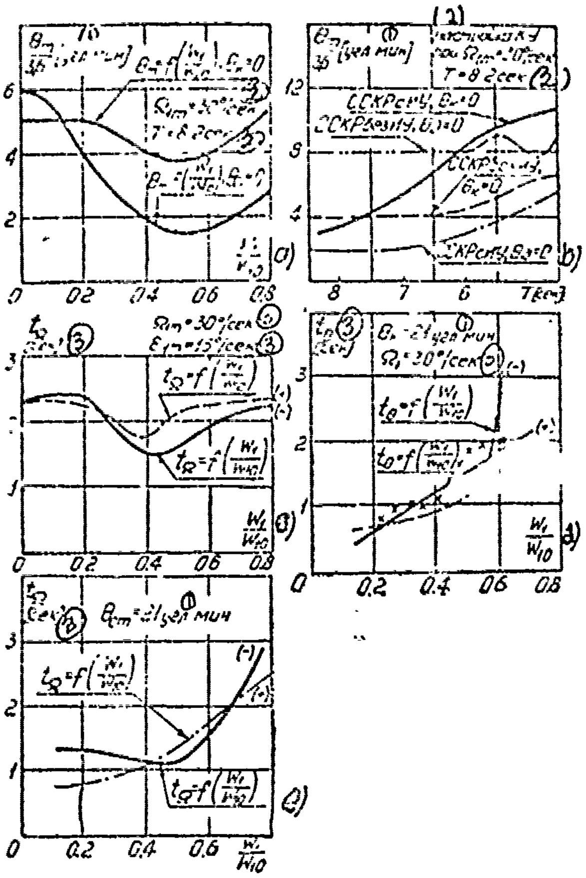

Fig. 3. Experimental schedules of operation of SSKR with IU.

Key: (1). [angl. min]. (2). Tuning of KU with ... s. (3). s.

Page 192.

Fig. 3a presents the dependences of the maximum value of error θ_m in function $\frac{W_1}{W_{10}}$ ($\frac{W_1}{W_{10}}$ - characterizes the position of the wiper of potentiometer, with the help of which is regulated the factor of

amplification of integrator) during the final adjustment of VV $\Omega_1(t)=30\sin\frac{2\pi}{\tau_2}t$ for the tuning of KS in dependences (1.4) and (1.5). From the analysis of graphs/curves it follows that during the tuning of KS on (1.5) the introduction/input of IU is more effective than during the tuning on (1.4). This is connected with the fact that the integrator of error is capable to ensure compensation only θ_κ.

Fig. 3b depicts dependences $\theta_m=f(T)$ for different structures of SSKR and different tuning of KS. Best on the accuracy is SSKR with IU during the tuning of KS on dependence (1.5). With an increase in frequency $\omega=\frac{1}{T}$ of change in VV error θ_m' in SSKR increases, since with an increase ω increases weight θ_m. Smallest change θ_m with change T is observed in SSKR without IU with the tuning of KS on (1.5).

Fig. 3c presents the dependences of transit time $t_n=f\left(\frac{W_1}{W_{10}}\right)$ during the final adjustment of VV (different signs) of the form

$$\theta_1(t)=\left.\begin{matrix}\frac{\varepsilon_{1m}t^2}{2} & \overset{(1)}{\text{при}}\ 0<t\leqslant\frac{\Omega_{1m}}{\varepsilon_{1m}},\\ \Omega_{1m}t & \overset{(1)}{\text{при}}\ t>\frac{\Omega_{1m}}{\varepsilon_{1m}}.\end{matrix}\right\} \quad (2.8)$$

Key: (1). with

Fig. 3d and 3e depicts respectively transit time $t_n=f\left(\frac{W_1}{W_{10}}\right)$, $t_n=f\left(\frac{W_1}{W_{1}}\right)$ during the final adjustment artificially created $\theta_\kappa=21$ minutes of angle and $\theta_{cm}=21$ minutes of angle. In the modes/conditions indicated the mean-quadradic error of SSKR with IU during the tuning of KS

according to the law (1.5) decreases 5-20 times in comparison with SSKR without IU.

From the analy. i of .ne dependences Fig. 3a-3e it follows that the optimum tuning of integrator for SSKR being investigated is $\frac{W_1}{W_{1n}} = 0{,}4 \div 0{,}5$

All given above results are obtained in the stationary parameters of SSKR.

However, the transiency of the parameters and the nonlinearity of the characteristics of elements/cells of SSKR with IU cause the disturbance of the conditions for compensation θ_{∂}, which can lead to increase θ_{∂} to the inadmissible value.

With the disturbance of condition $\varphi = \frac{1}{K}$ (change in the factor of amplification of K of SSKR or change in KS φ) $\theta_{\partial} \neq 0$ accepts the value

$$\theta_{\partial} = \varepsilon_1 \frac{1-(K \pm \Delta K)\varphi}{K_H(K \pm \Delta K)} = \mp \frac{\varepsilon_1 \frac{\Delta K}{K}}{KK_H\left(1 \pm \frac{\Delta K}{K}\right)} =$$

$$= \mp \theta_{\partial 0} \frac{\frac{\Delta K}{K}}{1 \pm \frac{\Delta K}{K}}, \qquad (2.9)$$

$$\theta_{\partial} = \varepsilon_1 \frac{1-K(\varphi \pm \Delta\varphi)}{KK_H} = \mp \varepsilon_1 \frac{\Delta\varphi K}{KK_H} = \mp \theta_{\partial 0} \Delta\varphi K. \qquad (2.10)$$

Page 193.

Fig. 1d depicts block diagram of SSKR with IU (I1), in which the part of KS, developed by differentiator (Dif1) and preliminarily rectified by rectifier (D), is multiplied in the block of product (BP1) by output signal $U_1\int\theta\,dt$ of integrator (I2) of actual error of SSKR. If $\theta_\partial=0$, then signal at output BP1 is equal to zero. If $\theta_\partial\neq0$, then at output BP1 appears the signal, which compensates for θ_∂. The presence of D in the circuit of KS ensures sign change at output BP1 with sign change in VV. I1 affects both the accuracy and stability of SSKR; target I2, BP1, KS affects the accuracy and oscillation property during the final adjustment of VV, but it does not affect stability and quality of the free transient processes when VV is absent. To the investigation of this diagram is dedicated the 3rd section of this article.

3. Investigation of work of SSKR with IU in presence of internal and external disturbances/perturbations.

In view of a continuous change of the parameters of transient SSKR in the process there is no its work, steady-state modes/conditions in the usual concept (with $t\to\infty$). However, by

analogy with stationary SSKR we will determine θ_K^3 when $\theta_1(t)=\Omega_1 t$, θ_U when $\theta_1(t)=\frac{\varepsilon_1 t^2}{2}$, θ_M with M(t)=M=const and so forth.

Let the work of SSKR (Fig. 1d) be described by the differential equation of form (with the initial zero conditions and the only the factor of amplification of system)

$$T_1T_2\frac{d^3\theta}{dt^3}+(T_1+T_2)\frac{d^2\theta}{dt^2}+\frac{d\theta}{dt}+K(t)\theta+$$
$$+K_HK(t)\int_0^t\theta\,dt+W_1K(t)\left|\frac{d\theta_1}{dt}\right|\left|\int_0^t\theta\,dt\right|=$$
$$=T_1T_2\frac{d^3\theta_1}{dt^3}+(T_1+T_2)\frac{d^2\theta_1}{dt^2}+$$
$$+[1-\varphi K(t)]\frac{d\theta_1}{dt}\mp M(t)\,K_M\mp\frac{dM(t)}{dt}K_MT_1. \qquad (3.1)$$

Equation (3.1) is nonlinear (contains product $\left|\frac{d\theta_1}{dt}\right|\left|\int_0^t\theta\,dt\right|$) also, with the variable parameter K(t). If we suppose that $\frac{d\theta_1}{dt}$ - in advance known function of time, and the time of integration I1, I2 identical, then equation (3.1) can be investigated in the first approximation, as linear with the variable coefficients, utilizing L. A. Zade's method [1] - [3].

After dividing left and right side (3.1) for the sum

$$\alpha(t)=K(t)\left[K_H+W_1\left|\frac{d\theta_1}{dt}\right|\right], \qquad (3.2)$$

where $\alpha(t)\neq 0$, and then it differentiated both parts of the equation

for independent by the variable/alternating t, we will obtain

$$A_0(t)\frac{d^4\Theta}{dt^4}+A_1(t)\frac{d^3\Theta}{dt^3}+A_2(t)\frac{d^2\Theta}{dt^2}+A_3(t)\frac{d\Theta}{dt}+A_4(t)\Theta=$$
$$=B_0(t)\frac{d^4\Theta_1}{dt^4}+B_1(t)\frac{d^3\Theta_1}{dt^3}+B_2(t)\frac{d^2\Theta_1}{dt^2}+$$
$$+C_0(t)\frac{d^2M(t)}{dt^2}+C_1(t)\frac{dM(t)}{dt}+C_2(t)M(t). \qquad (3.3)$$

Page 194.

From equation (3.3) it is possible to determine the conditions for the compensation for components Θ with the particular forms of VV

$$\Theta_M=\lambda_1 M=0, \quad (1)\text{ если при } t>t_k\ C_2(t)=0; \qquad (3.4)$$
$$\Theta_{M1}=\lambda_2\frac{dM}{dt}=0, \quad (1)\text{ если при } t>t_k\ C_1(t)=0,\ C_2(t)=0; \qquad (3.5)$$
$$\Theta_k=\lambda_3\frac{d\Theta_1}{dt}=0, \quad (1)\text{ если при } t>t_k\ B_3(t)=0; \qquad (3.6)$$
$$\Theta_\partial=\lambda_4\frac{d^2\Theta_1}{dt^2}=0, \quad (1)\text{ если при } t>t_k\ B_2(t)=B_3(t)=0; \qquad (3.7)$$
$$\Theta_{\partial 1}=\lambda_5\frac{d^3\Theta_1}{dt^3}=0, \quad (1)\text{ если при } t>t_k\ B_1(t)=B_2(t)=B_3(t)=0. \qquad (3.8)$$

Key: (1). if with.

In (3.4)-(3.8) t_k - the duration of pulse transient response of SSKR.

For the change in the time of factor of amplification of SSKR in the dependence

$$K(t)=\frac{1}{K_0+K_1 t} \qquad (3.9)$$

coefficients $C_1(t)$, $C_2(t)$, $B_1(t)$, $B_2(t)$, necessary for determining the conditions Θ_{M}, Θ_{M1}, Θ_{A}, Θ_{e}, Θ_{01}, take the form

$$C_1(t) = \frac{K_M\gamma_1}{\gamma} + \frac{K_M T_1\left[K_1\gamma - \gamma_1 W_1 \frac{d^2\Theta_1}{dt^2}\right]}{\gamma^2};$$

$$C_2(t) = \frac{K_M K_1\left[\gamma - \gamma_1 W_1 \frac{d^2\Theta_1}{dt^2}\right]}{\gamma^2},$$

$$B_1(t) = \frac{[\gamma_1 - \varphi + K_1(T_1 + T_2)]\gamma - \gamma_1(T_1 + T_2)W_1\frac{d^2\Theta_1}{dt^2}}{\gamma^2};$$

$$B_2(t) = \frac{\varphi K_1\gamma + (\gamma_1 - \varphi)\left[K_1\gamma - W_1\frac{d^2\Theta_1}{dt^2}\right]}{\gamma_1\gamma^2},$$

where $\gamma_1 = K_0 + K_1 t$, $\gamma = K_H + W_1\frac{d\Theta_1}{dt}$.

Table 1.

(2) Тип ССКР	(3) Режим работы ССКР	(1) Условия компенсации ошибок			
		$\theta_м$	$\theta_{м1}$	$\theta_к$	$\theta_э$
I КУ	(4) Свободный переходный процесс			—	—
	$\theta_1(t)=\Omega_1 t$	$C_2(t)= =K_м\gamma_1=0$	$C_1(t)=K_м T_1\gamma_1=0$ $C_2(t)=K_м\gamma_1=0$	$B_3(t)=\gamma_1-\psi=0$	—
	$\theta_1(t)=\frac{\varepsilon_1 t^2}{2}$			—	$B_2(t)=\gamma_1(T_1+T_2)=0$ $B_3(t)=\gamma_1-\psi=0$
II КУ+ПИ	(4) Свободный переходный процесс			—	—
	$\theta_1(t)=\Omega_1 t$	$C_2(t)= =\frac{K_м K_1}{K_И}=0$	$C_1(t)= =\frac{K_м\gamma_1+K_м T_1 K_1}{K_И}=0$ $C_2(t)=\frac{K_м K_1}{K_И}=0$	$B_2(t)=\frac{K_1}{K_И}=0$	—
	$\theta_1(t)=\frac{\varepsilon_1 t^2}{2}$				$B_2(t)=\frac{\gamma_1-\psi+K_1(T_1+T_2)}{K_И}=0$ $B_3(t)=\frac{K_1}{K_И}=0$

Key: (1). Conditions for error compensation. (2). Type of SSKR (3). Mode of operation of SSKR. (4). Free transient process.

Page 195.

Table 2.

(1) [illegible]			
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	$C_1(t) = K_H T_1 [illegible] = 0$	—	—
[illegible] $= 0$	$C_1(t) = [illegible] = 0$ $C_2(t) = [illegible] = 0$	$B_1(t) = [illegible] = 0$	—
[illegible] $= 0$	$C_1(t) = [illegible] = 0$ $C_2(t) = [illegible] = 0$	—	$B_1(t) = [illegible] = 0$ $B_2(t) = [illegible] = 0$
[illegible] $= 0$	$C_1(t) = [illegible] = 0$ $C_2(t) = [illegible] = 0$	—	—
[illegible] $= 0$	$C_1(t) = [illegible] = 0$ $C_2(t) = [illegible] = 0$	$B_1(t) = [illegible] = 0$	—
[illegible] $= 0$	$C_1(t) = [illegible] = 0$ $C_2(t) = [illegible] = 0$	—	$B_1(t) = [illegible] = 0$ $B_2(t) = [illegible] = 0$

Key: (1). Conditions for error compensation. (2). Type of SSKR. (3). Mode of operation of SSKR. (4). Free transient process.

Page 196.

Tables 1 and 2 present the conditions for compensation θ_M, θ_{M_1}, θ_κ, θ_δ for different structures of SSKR with standard VV (for simplification in the tables they are accepted designation $\gamma_1 = K_0 + K_1 t$; $\gamma_2 = K_H + W_1\Omega_1$; $\gamma_3 = K_H + W_1\varepsilon_1 t$).

From the analysis table 1 and 2 it follows:

1. In structure 1 (usual diagram of SSKR) even in the stationary parameters of SSKR $\theta_M \neq 0$, $\theta_{M_1} \neq 0$, $\theta_\delta \neq 0$, $\theta_\kappa = 0$ with

$$a)\ K_1 = 0,\ K_0 = \varphi,\ b)\ K_0 + K_1 t = \varphi + \varphi_1(t) = \varphi(t).$$

2. In structure II (SSKR, supplemented by IU) $\theta_M = 0$, $\theta_\kappa = 0$, in the stationary or slowly changing parameters of system ($K_1 \sim 0$). In all modes/conditions $\theta_{M_1} \neq 0$, $\theta_{\delta 1} \neq 0$. When $K_1 = 0$ θ_{M_1} accepts minimum value $\theta_{M_1} = \frac{h_M}{KK_H}$, $\theta_\delta = 0$ with $K_1 = 0$ and satisfaction of condition $K_0 = \varphi$.

3. In structure III (SSKR with tuning of KS according to the law $W_1\int\theta\, dt$) with $K_1 \neq 0$ or with $K_1 = 0$, but absence of VV $\theta_{M_1} \neq 0$, $\theta_{\delta 1} \neq 0$. With VV $\theta_1(t) = \Omega_1 t$, $\theta_1(t) = \frac{\varepsilon_1 t^2}{2}$ $\theta_M = 0$, if $K_1 = 0$. With VV $\theta_1(t) = \Omega_1 t$ $\theta_{M_1} \to 0$, if $K_1 = 0$ and $\Omega_1 \to \infty$. With VV $\theta_1(t) = \frac{\varepsilon_1 t^2}{2}$ $\theta_{M_1} \to 0$, if $K_1 = 0$ and $\varepsilon_1 t \to \infty$. $\theta_\kappa = 0$ with $K_1 = 0$. $\theta_\delta = 0$ with $K_1 = 0$ and satisfaction of condition $K_0 = \varphi$.

4. In structure of IV (SSKR, supplemented by KU, with tuning of KS according to the law $W_1\int\theta dt$) $\theta_M = 0$ with $K_1 = 0$; $\theta_M \to 0$ when: a) VV $\theta_1(t) = \Omega_1 t$, if $\Omega_1 \to \infty$; b) VV $\theta_1(t) = \frac{\varepsilon_1 t^2}{2}$, if $\varepsilon_1 t \to \infty$. $\theta_{M_1} \to 0$ with: a) $K_1 = 0$ and VV

$\theta_1(t)=\Omega_1 t$; if $\Omega_1 \to \infty$; b) $K_1=0$ and VV $\theta_1(t)=\frac{\varepsilon_1 t^2}{2}$, if $\varepsilon_1 t \to \infty$: $\theta_\kappa=0$ when $K_1=0$, $\theta_\kappa \to 0$, with VV $\theta_1(t)=\Omega_1 t$, if $\Omega_1 \to \infty$. $\theta_0=0$ with $K_1=0$ and satisfaction of condition $K_c=\varphi$.

The results of the investigation of effect of I1 on the quality of work of SSKR are represented by the graphs/curves of Fig. 3, and effects I2 - by oscillograms Fig. 4 and 5.

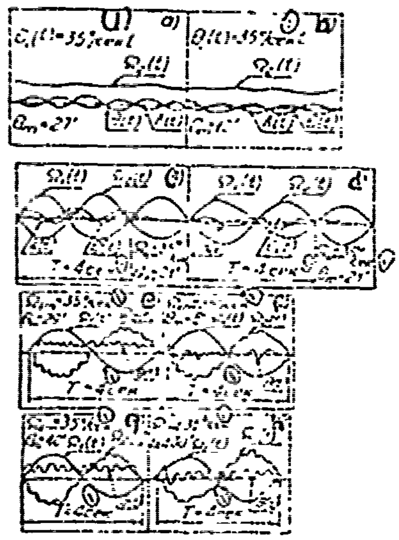

Fig. 4. Experimental oscillograms of work of SSKR with IU and tuning of KS according to the law $\int\theta_1 dt$.

Key: (1). s.

Page 197.

Fig. 4a and 4b presents final adjustment of VV $\theta_1(t)=\Omega_1 t$, while to Fig. 4c and 4d - VV $\theta_1(t)=\theta_{1m}\sin\omega t$ of SSKR with the I and III structures when disturbance/perturbation $\lambda(t)=\lambda\sin\omega t$ in the circuit of KS. Introduction I2 made it possible to reduce θ_k 2-3 times, and root-mean-square error σ_{θ_k} - в $5\div20$ for times.

Fig. 4d-4h presents work of SSKR with the I and III structures

with the pulse torque load M(t) with the pulse repetition rates f_1=2.5 Hz, f_2=5 Hz. Maximum value λ_m with introduction/input I2 descends 1.5-3 times, while θ_{ck} 5-20 times.

Fig. 5 depicts the oscillograms of work of SSKR I and the III structures in the case of the slowly changing parameters of system, i.e., in the case when working conditions can be formulated as follows: when $0<t<t_k$ are broken the conditions for compensation $\theta_1\left(\varphi \neq \frac{1}{K}\right)$, I2 it must ensure the elimination of the steady errors.

When $\theta_1(t)=\Omega_1 t$ and $\varphi \neq \frac{1}{K}$ $\theta_k=0$ (Fig. 5a). When $\theta_1(t)=\frac{\varepsilon_1 t^2}{2}$ (Fig. 5b) $\theta_1(t)=\Omega_1 t+\frac{\varepsilon_1 t^2}{2}$ (Fig. 5c) and $\varphi=\frac{1}{K}$ $\theta_\delta=0$ (by solid lines are represented processes in SSKR I of structure, and broken - in SSKR III of structure).

From the analysis of the obtained results it follows that introduction/input I1, I2 into SSKR is the effective means of the decrease of the effect of internal and external disturbances/perturbations on the accuracy of SSKR.

In structure IV it is expedient for the decoupling of work I1, I2 integrator I1 to switch on in the work only in the absence of VV.

Conclusion/output.

1. Following systems of combined control together with large advantages possess number of essential deficiencies/lacks, first of all: dependence of quality of work of system on change in ambient conditions and practical limitedness of number of derivatives of input effect.

2. It is expedient in number of cases to supplement combined control of integral.

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end section.